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"Recombination Coefficient of the Nighttime F-Region from Incoherent Scatter Measurements"

by

Donald Regis McCrory

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Submitted by: John S. Nisbet by J.J.B.
John S. Nisbet, Associate Professor of
Electrical Engineering, Project Supervisor

Approved by: A. H. Waynick by J.J.B.
A. H. Waynick, Director, Ionosphere Research
Laboratory

The Pennsylvania State University

College of Engineering

Department of Electrical Engineering

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ABSTRACT

Previous measurements of recombination coefficients in the F-region by Quinn and Nisbet (1965) were made using ion density profiles derived from reduced ionograms. Uncertainties resulted due to the lack of information on the profile of the top of the layer, on the temperatures of electrons, ions and neutral particles, and about the profiles in the lower F-region at night.

Profiles obtained at the Arecibo Ionospheric Observatory for one summer and one winter night have been used to study the night-time recombination. A considerable improvement in the consistency of the results is obtained by the use of the incoherent scatter measurements.

It is shown that the summer results compare closely with those obtained previously by Quinn and Nisbet (1965). It was found that in winter the electron content did not decrease and hence a different method was used to calculate the recombination coefficient than was used for the summer data. On this basis, it was quite difficult to make any conclusions about the seasonal dependence of the recombination coefficient.

I. INTRODUCTION

1.1 General Statement of the Problem

In previous investigations, Nisbet and Quinn (1963) and Quinn and Nisbet (1965) have examined the recombination and diffusion processes at night using electron density profiles reduced from ionograms.

For these analyses it was found necessary to study the layer as a whole because of the importance of downward transport of ionization through the maximum. This required that certain assumptions be made about the shape of the top of the layer, or at least about the changes in the content above the peak as a function of time. The reduced ionograms did not, of course, extend beyond the maximum.

At night ionograms are subject to errors at lower heights due to dispersion in the lower regions of the ionosphere. It is in this region that the dissociative recombination coefficient becomes important and it is here that the lower boundary conditions for the transport velocity are established. It was thus necessary to correct the profiles to the extent possible and this was done using a series of correction factors developed by Long (1962). These measurements were compared with neutral atmospheric temperatures estimated using the mean monthly 10.7 cm solar flux and a relation derived by Jacchia (1962) from satellite retardation studies.

Incoherent scatter measurements of the ionosphere provide measurements of the electron density above and below the maximum, measurements of the electron and ion temperatures, indicate the ionic mass and are not subject to dispersive errors in the lower ionosphere at night.

It is the purpose of the present study to use incoherent backscatter measurements made at the Arecibo Ionospheric Observatory to make estimates of the recombination and diffusion coefficients and to compare these results with those obtained by Quinn and Nisbet (1965) and with those obtained by other investigators.

1.2 Previous Related Studies

1.2.1 Recombination and Diffusion

Yonezawa (1955) concluded that a Chapman distribution of electron density would not change its form through electron-ion diffusion but the layer would move as a whole. He also showed that any initial distribution of electron density would tend to a Chapman distribution as time proceeded. In doing this he assumed that electron removal took place by an attachment type process with its rate coefficient independent of height but considered that even if the rate coefficient varied with height and electron removal was accomplished by a recombination process, his results would still hold.

Ratcliffe et al. (1956) pointed out that diffusion was the controlling factor in the vertical distribution of ionization in the upper F-2 region. They showed that between 250 and 350 km, the loss of electrons followed a linear law. The loss coefficient was found to decrease exponentially with height Z according to the Law:

$$\beta = 10^{-4} \exp\left[\frac{300 - Z}{50}\right]$$

They suggested that the level of maximum production was near the F1 peak and that larger ionization at higher levels was due to the exponential decrease with height of the loss coefficient as shown in the equation above.

Shimazaki (1957) has shown that above 300 km any distribution of electron density will tend to equilibrium within an hour under the influence of diffusion. He found that the Bradbury model of distribution was much better than the Chapman model. He concluded that:

1. An upward scale height gradient has an appropriate effect on the Bradbury F-2 layer.

2. Temperature variations have a definite effect upon the height of the layer.

3. A non-uniform "semi-diurnal" vertical drift velocity has a serious effect upon the daily variations in the F2 layer.

4. A non-uniform diurnal vertical drift velocity has no desirable effect except near the equator.

Gliddon and Kendall (1960) made some calculations assuming a linear attachment type loss and considering diffusion to be present in the ionosphere. Their calculations showed that Ratcliffe's linear attachment type loss process seemed to hold and they also expressed considerable support for Bradbury's (1938) hypothesis that the F1 and F2 regions were both produced by the same source of ionization.

Rishbeth and Barron (1960) using a computer technique considered equilibrium conditions to hold and investigated the various processes controlling the shape of the F-2 layer of the ionosphere. They point out that an upward drift tends to transport ionization from its level of origin to a level where the loss rate is smaller thus accounting for the electron density peak lying above the peak production of ionization level. The authors conclude from their work that:

1. If the only vertical drift was that caused by plasma diffusion, then:

    a. The peak of electron density would occur near the level where the loss rate and the diffusion rate $d = D/H^2$ were equal.

    b. At the peak and below it, the electron density would be given by $N = q/\beta$, just as though there were no diffusion.

    c. At levels more than one scale height above the electron peak, the electron distribution would be controlled by diffusion and assume an exponential form.

    d. Near the electron peak, the distribution would be approximately parabolic, with a thickness inversely proportional to the gradient of the function $\log (\beta/d)$.

2. The effects produced by a vertical drift depended on the ratio of its magnitude to the product H • d at the electron peak. The shape of the layer would not be greatly effected and unless the drift were quite strong the peak electron density would still be given by $N = q/\beta$.

3. The above conclusions would not be materially effected if the scale height varied with height.

Nisbet and Quinn (1963) showed for the first time that β was not a constant. They showed that β according to the Bradbury hypothesis was proportional to the molecular density and that according to various atmospheric models, the molecular densities at 300 km were going to vary by a factor of 30 or 40 over the solar cycle and by a factor of about 3 diurnally. Therefore β at a given altitude was not obviously going to be the same at night as it was in the day and that it would also vary over the solar cycle.

In a letter to the editor, Dalgarno (1964) revised his estimates of the diffusion coefficient of 0+ ions in atomic oxygen in view of some recent measurements made by Stebbings, Smith and Ehrhardt. The corrected values for the collision frequency and diffusion coefficients are presented in the following table.

Table I

Collision Frequencies ν And Diffusion Coefficients D of O^+ in O

Temperature ^oK	300	400	500	700	1000	2000
$(Dn \times 10^{18})cm^{-1} sec^{-1}$	3.3	3.9	4.5	5.7	6.9	9.6
$(\nu \times 10^{10}/n)cm^3 sec^{-1}$	4.7	5.0	5.7	6.3	7.3	10.0

Hanson and Patterson (1964) discussed the problem of maintenance of the nighttime F-layer. They said that it was possible in principle that the nighttime F-layer could be maintained either by H^+ ions in the protonosphere providing a source of 0^+ ions through charge exchange, or by an upward drift of ionization which would raise the layer to an altitude where recombination was slow. They proceeded to show that, on the average, the number of H^+ ions that would be consumed by a charge exchange process could not be supplied by upward diffusion in the daytime. They therefore concluded that the protonosphere could not maintain the nighttime F-layer since it was not possible during the day to generate enough return flux of protons and that therefore it seemed most likely that the region was maintained by a vertical drift of ionization to a region where the recombination was relatively slow.

Quinn and Nisbet (1965) used mean monthly true height electron density profiles to arrive at estimates of the recombination and diffusion coefficients. This method, however, has certain drawbacks which were discussed by the authors. First of all, the authors were forced to use mean monthly electron density profiles which were reduced from ionograms and hence had no measurements of the profiles above the maximum. So a top to the profile had to be assumed. They found, however, that if the layer shape remained uniform and the effects of temperature changes were included that the calculation of β_{300} would not depend critically on the profile assumed for the top of the layer.

Coupled with this drawback, however, is the effect of determining temperatures from the profiles. For if the temperature changes are not accurately determined, then the recombination coefficients may be seriously in error. This effect is also coupled with the effect of a change in the electron-ion temperature ratio.

The effects of a decreasing T_e/T_i ratio and different assumptions about the changing shape of the layer were investigated. However, because the data used (bottom-side ionospheric soundings) did not provide any information on the shape of the top of the layer, no final conclusions could be drawn.

The effect of using the correct quadratic loss coefficient in the calculations was also considered. Since a wide range of values had been reported up to that time for this coefficient, the authors adopted a best estimate which would give the most consistent results for their diffusion velocity analysis.

The authors analysis was further complicated by the effects of low-lying ionization. To circumvent this problem they applied a correction due to Long (1962) to the profiles. This complication is tightly coupled to the previously mentioned quadratic loss coefficient since they both are effective at lower altitudes.

Utilizing the above mentioned assumptions, the authors arrived at the values of the recombinations coefficient listed in Table IV, Appendix. They found the following value for the diffusion coefficient:

$$D = \frac{(0.5 \pm 0.3)10^{17}}{n(M)} \sqrt{T}\, \mathrm{Sin}^2 I (\mathrm{cm}^2 \mathrm{sec}^{-1})$$

1.2.2 Transport

Martyn (1947) in attempting to account for the peculiar morphology of the F2 region had introduced the concept of ionization transportation by considering the continuity equation as

$$\frac{\partial N}{\partial t} = q - \beta N - \mathrm{div}(N\bar{v}).$$

where $\bar{v}$ was the transport velocity of the electrons (and ions).

Martyn (1959) pointed out three possibilities for the origin of the transport velocity:

1. The air in the region might possibly be in motion thus carrying the ionization with it.
2. If an electric current were present, the ionization would drift with the velocity vector.
3. The ionization diffuses under the influences of gravity and of its own partial-pressure gradient.

He then came up with the following equation which considered contributions from all the transport processes enumerated above:

$$\frac{\partial N}{\partial t} = q(z,t) - \beta(z)N + \frac{2g\,\mathrm{Sin}^2 I}{H_o \nu_i(z)}\left[\frac{\partial^2 N}{\partial Z^2} + \frac{3}{2}\frac{\partial N}{\partial Z} + \frac{N}{2}\right] - \bar{w}\frac{\partial N}{\partial Z} - \mathrm{div}\,(\bar{\mu}\,N)$$

where $\bar{w}$ = vertical drift velocity due to a current in the region.

Ferraro (1961) has reviewed work done on diffusion in the ionosphere. He summarized the results of Gliddon and Kendall's (1960) investigation as follows:

1. The peak electron density was increased by upward and decreased by downward drift. Between sunrise and noon, however, they found that the maximum density was little effected by drifts.

2. Upward drift raised and downward drift lowered the constant nighttime level h_m.

3. Downward drift tended to produce symmetry both of N_m and of h_m about noon.

4. Upward drift tended to produce a symmetry (i.e. N_{max} occurred at a time nearer sunset than noon while h_m decreased sharply at sunrise and rose slowly to reach the nighttime value between sunset and midnight).

Rishbeth (1961) assumed an isothermal ionosphere and showed that the height at which dn/dt was greatest was lowered when diffusion was present but the peak value of dn/dt was only slightly reduced. It was further shown that at sunrise the inclusion of diffusion in the determination of density profiles served to decrease the height at which the peak occurred but effected the magnitude of the peak only slightly. In doing this, the author used a continuity equation of the form:

$$dn/dt = q - \beta N - M_D - M_E$$

where βN = loss

M_D = term due to plasma diffusion

M_E = term due to electromagnetic drifts

q = production term

and a production equation as follows:

$$q(Z,\psi) = q_o \exp\,(1 - Z - e^{-Z} CH\psi).$$

He illustrated with graphs the fact that near sunrise the change in electron density showed a linear increase as the solar zenith angle decreased. He further pointed out that at sunrise dn/dt was primarily determined by the production q but that its magnitude was altered somewhat by β and the height of its peak was altered slightly by diffusion as pointed out previously. He also concluded that vertical drifts due to electromagnetic forces have little effect upon the peak values of dn/dt and electron density but did slightly modify the heights at which they occurred.

Garriot and Thomas (1962) wrote the continuity equation in the form $\frac{\partial N}{\partial t} = Q - L - M$ where $M = M_D + M_E = \mathrm{div}(N\overline{w})$. $\overline{w}$ was the total drift = $\overline{w}_D + \overline{w}_E$, i. e. the drifts due to diffusion and electrostatic fields, respectively. They then assumed negligible horizontal variations in N and $\overline{w}$ and that the electromagnetic drift velocity was independent of height in the F region so that at night the continuity equation could be written:

$$\frac{\partial N}{\partial t} = -\beta N + D\left[\frac{\partial^2 N}{\partial h^2} + \frac{3}{2H}\left(1 + \frac{5}{3}\gamma\right)\frac{\partial N}{\partial h} + \left(\gamma^2 + \frac{5}{2}\gamma + 1\right)\frac{N}{2H^2}\right] - \bar{v}\frac{\partial N}{\partial h}$$

They then made various assumptions about the values of the constants involved and using results from N(h, t) profiles were able to calculate the electromagnetic drift velocity ($\bar{v}$) on quiet nights. At Puerto Rico, drift velocities of the order of about 30 m/sec were found in summer but these were nearer 15 m/sec at equinox. It should be remembered however, that the results arrived at were highly dependent on the assumed value of the recombination coefficient β.

Kendall (1962) derived the form of the diffusion operator for the earth's magnetic field, which was approximated as a dipole field. Beginning with the continuity equation,

$$\frac{\partial N}{\partial t} = Q - L - \operatorname{div}(N\,\bar{v}_i)$$

the author defined the diffusion operator $\mathcal{D}$ by the equation,

$\frac{\partial N}{\partial t} = Q - L + D\mathcal{D}N$. After some mathematical manipulation, the author arrived at the following equations:

Variable	operator N
q	$\frac{\sin^2 I}{2H^2}N - \frac{3q}{Hr}\frac{\partial N}{\partial q} + \frac{4q^2}{r^2\sin^2 I}\frac{\partial^2 N}{\partial q^2} + \frac{\Gamma N}{Hr\,\Delta 4}$
θ	$\frac{\sin^2 I}{2H^2}N + \frac{3\cot\theta}{aH\Delta^2}\frac{dN}{d\theta} + \frac{1}{a^2\Delta^2\sin^2\theta}\frac{d^2N}{d\theta^2} + \frac{\Gamma N}{aH\Delta^4\sin^2\theta}$
r	$\left[\frac{2(a-r)}{4a-3r}\left(\frac{1}{H} + \frac{d}{dr}\right) + \frac{15r^2-40ar+24a^2}{r(4a-3r)^2}\right]\left(\frac{N}{H} + 2\frac{dN}{dr}\right)$

The notation used was:

$$\mu = \mathrm{Cos}\theta$$

$$\Delta^2 = 1 + 3\mu^2$$

$$\Gamma = 15\mu^4 + 10\mu^2 - 1$$

$$q = \frac{r_o^2 \ \mathrm{Cos}\theta}{r^2}$$

$$r = a \sin^2\theta$$

Near the equator of course, $\mu = o$ and the equations could be simplified.

Ferraro (1964) considered ambipolar diffusion in the presence of a magnetic field and refuted statements made by Chandra (1964) that there were certain discrepancies in the current theory of ambipolar diffusion in the ionosphere in the presence of a magnetic field. The author showed that the velocity of ions perpendicular to the vertical plane parallel to the magnetic field vector was given by:

$$v_i = \frac{\omega_x \ \nu_i}{\nu_i^2 + \omega_z^2} \ W_i$$

where

$$\omega_x = \frac{e \ B_x}{m_i}$$

$$\omega_z = \frac{e \ B_z}{m_i}$$

ν_i = collision frequency

W_i = velocity in z direction

He further demonstrated that the velocity in the x direction was given by:

$$\mu_i = \frac{\omega_z v_i}{\nu_i} = \frac{\omega_x \ \omega_z}{\nu_i^2 + \omega_z^2} \ W_i$$

which for $\nu_i \ll \omega_z$ (as is the case in the F-2 region) reduced to:

$$\mu_i = W_i \mathrm{Cot}\, I$$

Therefore the velocity of the ions (and hence the electrons) in the xz - plane will be mainly parallel to the magnetic field. He further pointed out that as $\nu_z/\omega_z \longrightarrow 0$, $v_i \longrightarrow 0$ so that in the limiting case, the flow of electrons was entirely along the lines of force.

Utilizing the equations of motion, the author proceeded to show that the vertical velocity of diffusion was given by:

$$W = -D \,\mathrm{Sin}^2 I \left(\frac{1}{n} \frac{\partial n}{\partial z} + \frac{1}{H_i} \right)$$

where $D = \dfrac{2\,kT}{m_i \nu_i}$ and $T_e = T_i$.

In the ionosphere, where horizontal currents can flow unimpeded, the author pointed out that the drift velocity in the y direction will be opposite for ions and electrons, thus constituting an electric current flow. He showed that the electric current density would be:

$$j \cong \frac{2nKT}{B_Z} \left(\frac{1}{n} \frac{\partial n}{\partial Z} + \frac{1}{H_i} \right) \mathrm{Sin}\, I \,\mathrm{Cos}\, I$$

Then he showed that utilizing normal values for these parameters resulted in the fact that the magnetic field of the drift currents in the ionosphere caused by the vertical diffusion of the plasma was negligible.

Kendall (1964) took exception to the fact that Chandra (1964) stated that he (Kendall) and others had assumed $\overline{v}_e = \overline{v}_i$ and therefore their work was based on a faulty equation. On the contrary, Kendall stated that he had not made this assumption. He further felt that putting $\overline{v}_i = \overline{v}_e$ (as Chandra had done) before solving the equation of motion may be incorrect.

The author concluded that:

(i) In the F 2 layer the relative velocity of ions and electrons was small.

(ii) Although the relative velocity of ions and electrons was small, the Lorentz Force $\overline{J} \times \overline{B}$ (where $\overline{J}$ = ne $(\overline{v}_i - \overline{v}_e)$ was large enough to balance the small gravitational forces and pressure gradients acting.

(iii) The velocity of electrons (and ions) at right angles to a line of force was $v_i^{\perp} = \overline{E} \times \overline{B}/B^2$ (where $B = |\overline{B}|$ and $\overline{E}$ was the electric field arising from the dynamo region).

1.2.3 Production

Rishbeth and Setty (1961) utilised observational data taken at Slough and Cambridge to investigate the F-layer at sunrise. Using this data, it was observed that the rate of increase of electron density (dn/dt) just after sunrise was greater in winter than in summer, and also greater at sunspot maximum than at sunspot minimum. It was felt that this seasonal anomaly in dn/dt was connected with the well known fact that in northern latitudes the noon F2-layer electron density is greater in winter than in summer (the "winter anomaly"). They found that the increase in electron density began in summer when the solar zenith angle was approximately 92^{o} and in winter when the solar zenith angle was approximately 96^{o}. Shortly after the increase began, the change in electron density (dn/dt) became linear for about two hours.

Utilizing the continuity equation $dn/dt = q - L$ the authors neglect vertical movements in their analysis. Furthermore, at sunrise, the production term is of major importance in the continuity equation so that the continuity equation at sunrise reduces to $dn/dt = q$. Since f is dependent on both the ratio of 0 to N_2 and their ionization cross-sections, any change in ratio of 0 to N_2 directly effects the production and hence the rate of change of electron density at sunrise. The authors therefore propose that it is this change in composition of the upper atmosphere that causes the seasonal anomaly in the F-region and hence accounts for the seasonal anomaly observed in dn/dt at sunrise.

Hinteregger and Watanabe (1962) have set forth the following suggested EUV flux groups which have an effect upon the ionosphere.

1. Group I (911-1027A) penetrates to relatively low altitudes to ionize 0_2.

2. Group II (796-911A) creates mostly 0^+ above 140 km. However, the lifetime of 0^+ in the F region is relatively short compared to higher altitudes due to ion-atom interchange and subsequent dissociative recombination.

3. Group III (465-630A) seems to have the most effect above about 200 km where atomic oxygen is the dominant constituent. Variations in this groups intensity seem to be a function of time over the 11-year solar cycle and perhaps even the 27 day period of the sun's rotation.

4. Group IV (280-370A) seems to penetrate slightly deeper than Group III and is clearly the dominant group in the 130-150 km range.

The authors concluded that of the above mentioned groups, Group III contributed most significantly to F-region ionization although all groups with the exception of Group I, join in 0^+ production.

Watanabe and Hinteregger (1962) have concluded that electron production in the F-region is primarily due to ultraviolet radiation in the range 170-900A. The authors have made a study of the photoionization rates as a function of altitude and solar zenith angle. From this study, it was calculated that at sunrise (i. e. $\psi = 90^o$) the maximum ionization would be at approximately 320 km. As the sun came up, however, the location of the maximum ionization descended rather rapidly to the F_1 region ($\simeq$ 150 km). The F_2 electron-density peak didn't correspondingly shift downward however due to the higher recombination rates found at lower altitudes.

Nicolet and Swider (1963) pointed out that the following ionization processes are the chief ones occurring in the F-region:

a) Ionization of N_2 for $\lambda < 796$ Å with absorption cross-section greater than 10^{-17} cm^2.

b) Ionization of 0 for $\lambda < 796$ Å subject to the absorption of N_2.

c) Ionization of 0 for $\lambda < 800$ Å with different absorption cross-sections for its different ionization potentials at 910 Å, 732 Å, and 665 Å.

They further stated that an exact analysis of the ionization problem in the F-region required a simultaneous knowledge of the energy of solar emissions and of the absorption cross-sections of 0, N_2 and 0_2. They felt that, in particular, the penetration of monochromatic solar radiations between the E and F1 peaks must be known in order to determine the exact behavior of the electron production but that this was difficult information to obtain due to the variations in solar activity.

It was also pointed out that the dissociative recombination coefficient (α) of the various important constituents was not known very accurately but that since the electron-ion collision frequency decreased with temperature ($\propto T^{-3/2}$), the normal tendency of the temperature dependence of α_D should be to decrease with increasing temperature.

Nicolet and Swider pointed out that 0^+ is transferred into molecular ions by ion-atom interchange but 0^+ production is increased by the charge transfer process between atomic oxygen and molecular nitrogen ions.

Willmore (1964) has examined 51,000 satellite measurements of electron temperature and density made during April 27-June 18, 1962, in order to examine the energy source required to produce the observed temperature distribution.

Willmore found that the observed energy input fell with latitude approximately as the cosine of the solar zenith distance at noon while the electron temperature increased with latitude due entirely to a fall in electron density which also occurred. He found that this latitude effect persisted even at night and suggested that this showed there is still a source of energy after sunset (the magnitude being about 2-3 per cent of that in the daytime).

He then concluded that the observed features of the electron temperature distribution can be accounted for by the heating due to trapped electrons with energies of 2-3 Kev in fluxes of about 8×10^9 cm^{-2}sec^{-1}, supplemented during the day by photo-electrons produced by sunlight provided due allowance is made for the effects of escaping photo-electrons spiralling upwards along the lines of force.

Garriott and Smith (1965) have used data from Syncom III transmissions obtained at Hawaii and Stanford to obtain an integrated production rate. This was accomplished by utilizing sunrise data and assuming that the integrated loss term in the continuity equation was negligible at night and for at least 30 minutes after ground sunrise. The divergence terms were neglected since N = 0 at both low and very high altitudes. Therefore, the continuity equation was reduced to an integrated electron density and a production term which was dependent on the Chapman function. Using this method, an integrated production rate for an overhead sun was found to be $1.4\ (\pm\ 0.3) \times 10^{14}$ electrons/m^2/sec in the autumn of 1964. This corresponded to a peak q_o of approximately 1.3×10^9 electrons/m^3/sec for a single constituent atmosphere.

1.3 Specific Statement of the Problem

The primary objective of this study is to measure the rates of recombination, diffusion, and drift in the F-region from incoherent scatter sounding profiles. In particular this investigation will attempt to resolve some of the assumptions made in the previous analysis by Nisbet and Quinn (1963) and Quinn and Nisbet (1965). These assumptions had to be made because of the incompleteness of their data. These assumptions, of course, have a direct effect upon the values of the recombination and diffusion coefficients cited in the above mentioned works, and hence it is desirable to eliminate as many of them as possible. The major difficulties encountered were as follows.

1.3.1 Effect of the Shape Assumed for the Top Profile

The objective here is to arrive at electron density profiles which give the best approximation to the true profile. This had not been possible in the previous analysis by Quinn and Nisbet (1965) because they were forced to use electron density profiles reduced from ionograms. These profiles of course did not extend above the maximum and it was therefore necessary to assume that the top profile followed some sort of functional form such as a Chapman $C\alpha$ profile. The top profile however gives an indication of the ion temperature and it is therefore of considerable importance to know the shape of the profile as accurately as possible.

1.3.2 Effect of Determining Temperatures from the Profiles

The problem here is to arrive at the temperatures in the ionosphere as precisely as possible. The temperatures are not only important in the construction of the neutral atmosphere but also a knowledge of the temperatures may give an indication of what the heating mechanisms were that produced the temperatures.

Previously, Quinn and Nisbet (1965) used a relation between the mean monthly temperature and the 10.7 cm solar flux given by Harris and Priester (1962) to arrive at the temperatures. They also used another method which utilized the thickness parameter scat to determine the temperature from the electron density profiles and found that temperatures deduced from this relation were systematically lower than temperatures determined from the 10.7 cm solar flux. Hence it appears that some ambiguity exists here and it is therefore desirable to arrive at the temperatures by a more direct approach.

1.3.3 Effect of the Quadratic Loss Coefficient

The quadratic loss coefficient ($\propto$) is extremely important in the lower portion of the F-layer. A wide range of values has been reported for this coefficient in the literature and therefore it appears to be one of the major uncertainties in this work as well as that performed by Quinn and Nisbet. It is therefore desirable to arrive at an estimate of the quadratic loss coefficient which gives the most consistent results with respect to the diffusion velocity profiles.

1.3.4 Effect of Low-Lying Ionization

The objective here is to insure that the effects of low-lying ionization are taken into account when the profiles are determined. If the T_e/T_i ratio is high in the low regions then the density measurements will be affected. Quinn and Nisbet (1965) used a correction due to Long (1962) to correct their profiles at the lower altitudes. It is here, however, that the quadratic loss coefficient is important and here that the lower boundary conditions for the diffusion velocity are established. Therefore it is very important to have profiles that are as accurate as possible so that corrections are not necessary.

1.3.5 Effect of Change in T_e/T_i

The objective here is to study the cooling during the night to look for sources of ionization. In other words by studying the change in T_e/T_i throughout the night, it may be possible to arrive at some conclusions about what is causing the production during the night.

2. METHOD OF ANALYSIS

2.1 Theoretical Background

2.1.1 Method of Data Reduction

Gordon (1958) suggested that radio waves incident upon the ionosphere at frequencies well above the critical frequency would be scattered by irregularities in the electron densities. He therefore proposed that a powerful radar could detect the incoherent backscatter from the free electrons in the ionosphere and hence the electron density profile could be measured. He further suggested that since Doppler shifts in frequency would result from the thermal motion of the electrons, the electron temperatures could be deduced by measuring the width of the spectrum of frequencies returned from a given volume.

This is the basic principle behind the method used for obtaining electron density profiles and electron and ion temperatures from incoherent backscatter experiments conducted at Arecibo, Puerto Rico and other similar installations around the world. Much has been written on this subject by workers in this field (i.e. Pineo and Briscoe (1961), Salpeter (1960), Evans (1962), Laaspere (1959), Fejer (1960), and others) and therefore no detailed discussion of the method will be undertaken here. However, it is felt that a brief discussion is necessary concerning what is measured with reference to how T_e and T_i are obtained from the spectra and how n_e is obtained from the power densities.

At Arecibo a radar pulse-width of 500μs is normally used for obtaining spectra for altitudes below approximately 500 km. A pulse is transmitted, backscattered by the ionosphere and subsequently processed by the receiver. Gating of the receiver is performed to obtain spectra at various altitudes. Each altitude is probed for approximately two minutes. The returned signals are processed by the receivers and arrive at a spectrum analyzer having 100 narrow filters each centered 200 cycles from the next. The averaged output from the spectrum analyzer over a two minute period is combined to give a spectra plot from which the T_e/T_i ratio and T_i may be determined. The half-power bandwidth of the spectra and the peak-to-valley ratio give an indication of the ion temperature and the T_e/T_i ratio. Moorcroft (1964) has discussed the reduction of these spectra at length.

The electron density profiles are obtained as follows. Signals are transmitted with pulse widths which can be selected to provide the required degree of resolution compatible with the sensitivity and integrating times desired. The returned signals are received and sampled by a digital voltmeter, the output of which is connected to a digital computer which records and integrates the received signal. The length of time of integration is a matter of choice but it has been found that intervals of five minutes or longer give reasonably accurate electron density profiles. Two receiver channels are used to deduce the final profiles. The density channel processes the received signals and delivers them to the computer for integration. Simultaneously, the recovery channel processes the signals and gives an indication of any receiver recovery problem that may exist due to gating of the receiver. The signals processed by the recovery and density channels are then combined in the computer to subtract from the electron density profiles any residual due to receiver recovery. Finally each resulting profile is normalized so that the peak electron density corresponds to the peak electron density determined from ionosonde records which are taken simultaneously.

2.1.2 Procedure

Data is being obtained at Puerto Rico for three winter days (a day corresponds to a thirty hour period) and three summer days every year for the next several years. By obtaining both winter and summer data over the solar cycle, it is felt that the seasonal dependence (for varying solar conditions) of both the recombination and diffusion coefficients may be obtained. Computer programs have been written which compute the diffusion and recombination coefficients utilizing the method developed by Nisbet and Quinn (1963). The present work was done using data from one winter and one summer day.

The densities for the following work were obtained using a transmitter pulse width of 100 μ sec. The receiver and gate delays were such that for the summer data, densities were obtained every 15 km over the altitude range from approximately

100 km to 750 km. For the winter data, densities were obtained every 30 km over the altitude range from approximately 100 km to 1150 km.

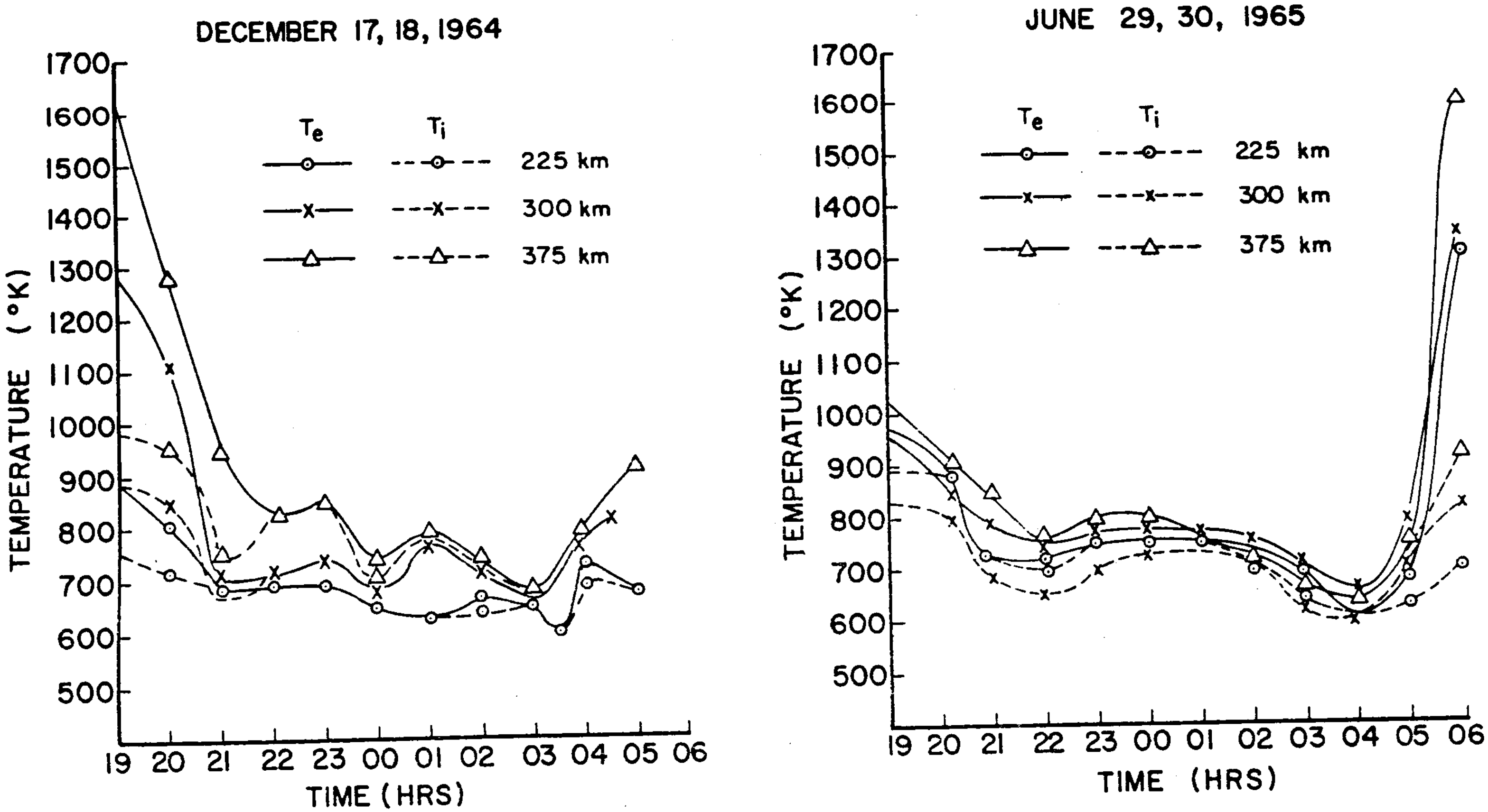
Spectra were obtained using a 500 μ sec transmitter pulse width which resulted in a 75 km height resolution. Hence temperatures (T_e and T_i) were obtained at 225 km, 300 km, 375 km, and 450 km. For the calculations, it was assumed that the T_e/T_i ratio decreased linearly to one at 150 km and 600 km.

2.2 Analysis of Experimental Data

2.2.1 Shape of the F Region Above the Maximum

The shape of the electron density profile above the maximum in the region where diffusion effects dominate and atomic oxygen is the major ion is dependent on the sum of the electron and ion temperatures. Figure 1 shows electron and ion temperatures for one summer and one winter night. In winter the electron temperatures in the ionosphere decrease steadily and become essentially equal to the ion temperatures throughout the major portion of the night. These temperatures are seen to decrease rather steadily until approximately 3:00 at which time the ion and electron temperatures begin to increase.

In summer the electron temperatures drop rapidly in the first two hours after sunset and then remain relatively constant throughout the night. It can be seen on the plot that the electron temperature has stabilized at a slightly higher



ION AND ELECTRON TEMPERATURES FROM BACKSCATTER

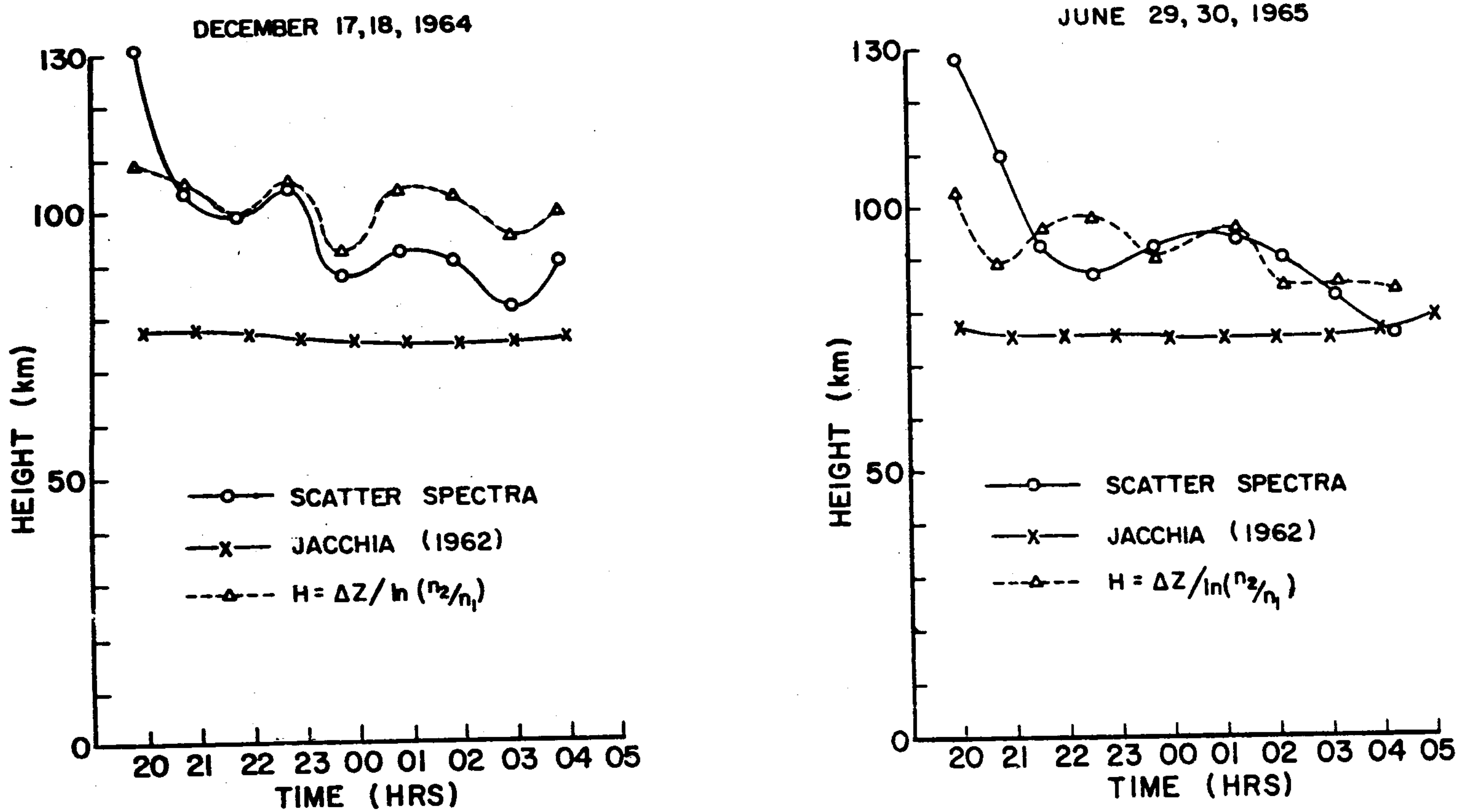
FIGURE 1

value than the ion temperature throughout most of the night at 300 km. At approximately 04:00 hours, the electrons are seen to begin heating up and rise rather rapidly thereafter.

Figure 2 shows comparative values of the plasma scale height calculated for a summer night. Values are given calculated from electron and ion temperatures measured using the incoherent backscatter spectra assuming O^+ as the major ion, from the relation given by Jacchia (1962) assuming that T_i and T_n are equal, and from the slope of the electron density profile at 450 km. It is apparent that on the summer night investigated, the plasma scale heights calculated using the incoherent scatter spectra are larger than those calculated under the assumption that T_e, T_i and T_n are equal. More important perhaps is the change in scale height as a function of time, for this controls the downward flux of electrons through the maximum. If such an effect is not taken into account for recombination coefficients calculated from profiles below the maximum, the resulting recombination coefficients will be underestimated. The winter night shows essentially the same type variations as observed in the summer.

2.2.2 Effects Related to the Lower F-Region

In the previous analysis by Quinn and Nisbet (1965), mean monthly ionograms were used which had been calculated by a modified Budden method. Such profiles have been shown to result in an underestimation of the electron densities



PLASMA SCALE HEIGHTS

FIGURE 2

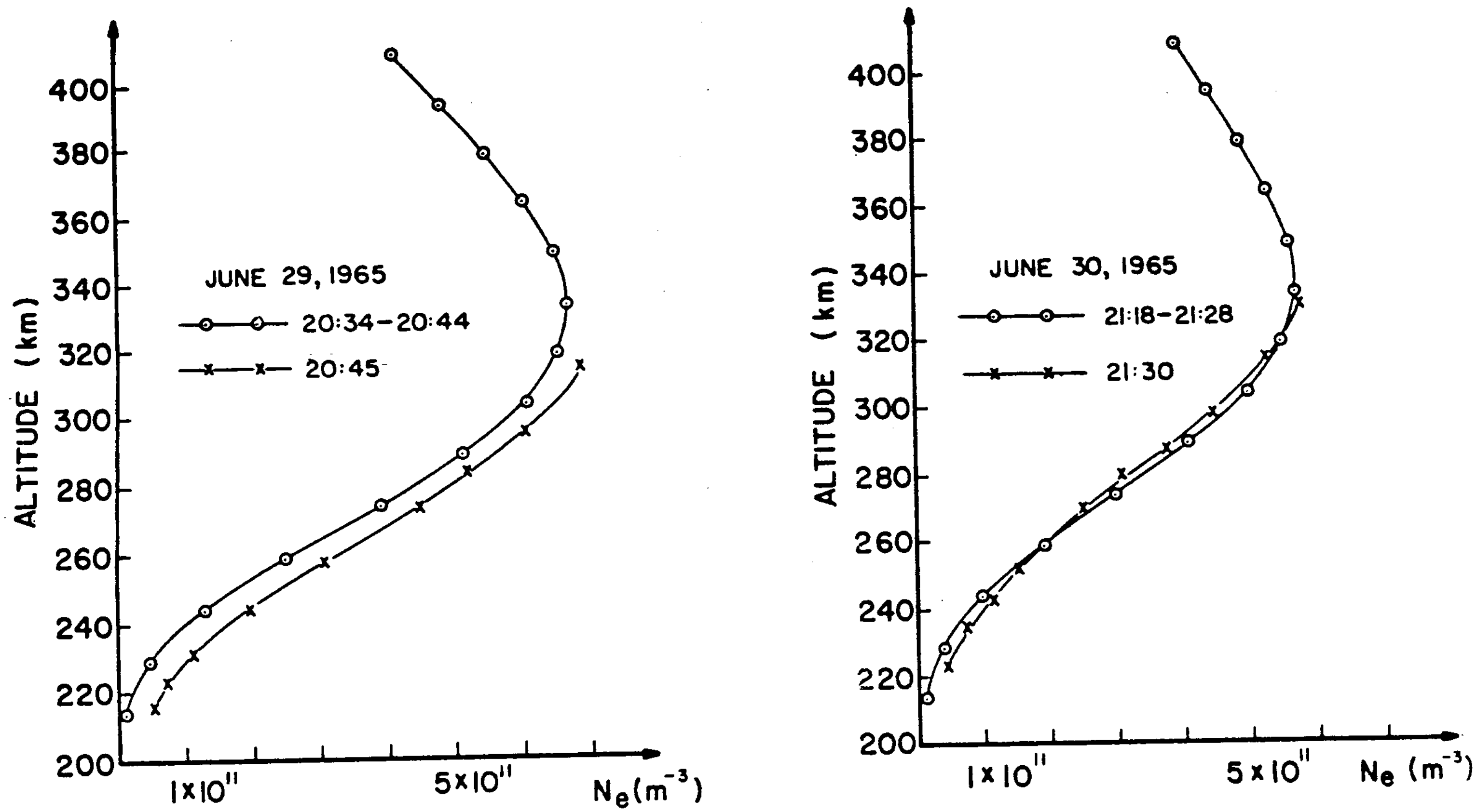
at low heights and hence a correction based on the work of Long (1962) was applied.

In the present analysis incoherent backscatter profiles have been used which do not suffer from these disadvantages. Figure 3 shows electron density profiles measured at night using the incoherent scatter profiles. On these same graphs, profiles are included which were reduced from ionograms taken at approximately the same time using a reduction method developed by Doupnik and Schmerling (1965). It is quite evident that the profiles from the backscatter and reduced ionogram methods are very similar.

In the previous work, diffusion coefficients were calculated. The decay in the electron densities at night was related to the recombination coefficient using neutral atmosphere models. These coefficients allowed the continuity equation to be integrated up to given heights to determine ion fluxes or ion velocities. By comparing these ion velocities with normalized diffusion velocities calculated from the shape of the profile, diffusion coefficients were calculated.

This type of calculation is extremely sensitive to the assumptions made about the effect of the correction applied. It was therefore considered of considerable importance to repeat the analysis with more accurate data.

Figures 4 and 5 show the vertical and normalized diffusion velocities calculated at approximately the same time



○ ELECTRON DENSITY PROFILES FROM INCOHERENT BACKSCATTER

× TRUE HEIGHT PROFILES FROM IONOGRAMS

FIGURE 3

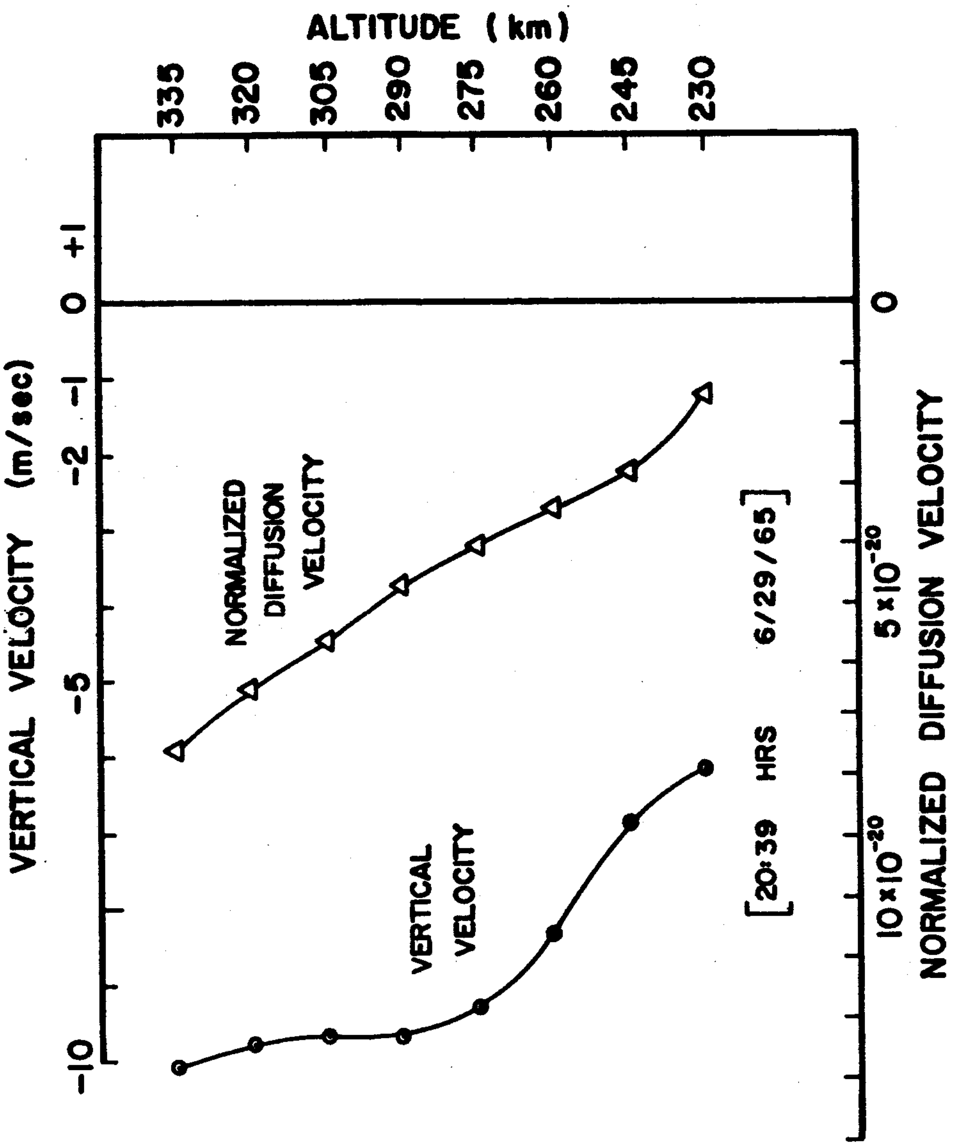

VERTICAL VELOCITY (m/sec)
-10
-5
-2
-1
0
+1
ALTITUDE (km)
335
320
305
290
275
260
245
230
NORMALIZED DIFFUSION VELOCITY
VERTICAL VELOCITY
[20:39 HRS 6/29/65]
10×10^-20
5×10^-20
0
NORMALIZED DIFFUSION VELOCITY

FIGURE 4

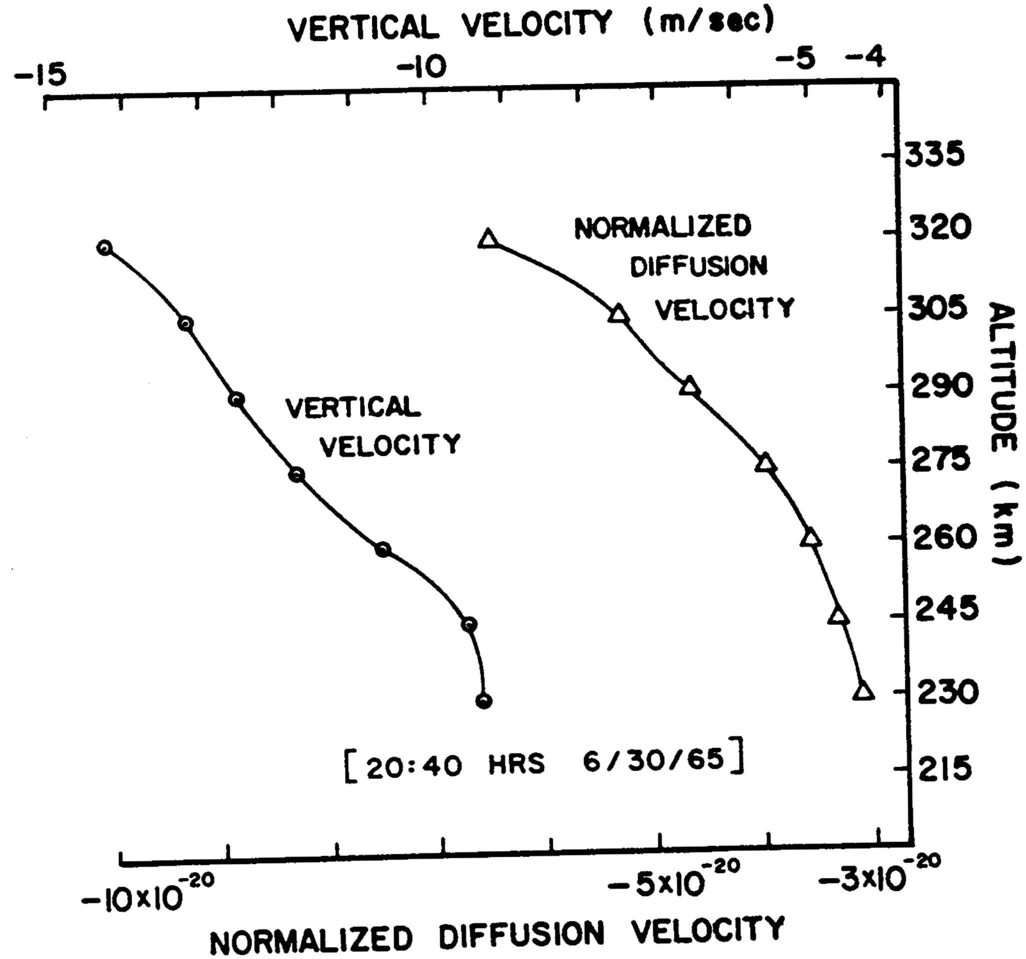

VERTICAL VELOCITY (m/sec)
-15
-10
-5
-4
335
320
305
290
275
260
245
230
215
ALTITUDE (km)
NORMALIZED
DIFFUSION
VELOCITY
VERTICAL
VELOCITY
[20:40 HRS 6/30/65]
-10x10^-20
-5x10^-20
-3x10^-20
NORMALIZED DIFFUSION VELOCITY

FIGURE 5

on two consecutive nights (June 29, 30, 1965) during the summer. The diffusion coefficients calculated from these velocity profiles were:

$$D = \frac{0.398 \times 10^{19} \sqrt{T} \, \mathrm{Sin}^2 I}{n(M)} \quad m^2 \, sec^{-1} \qquad [20:39 \text{ hrs} - 6/29/65]$$

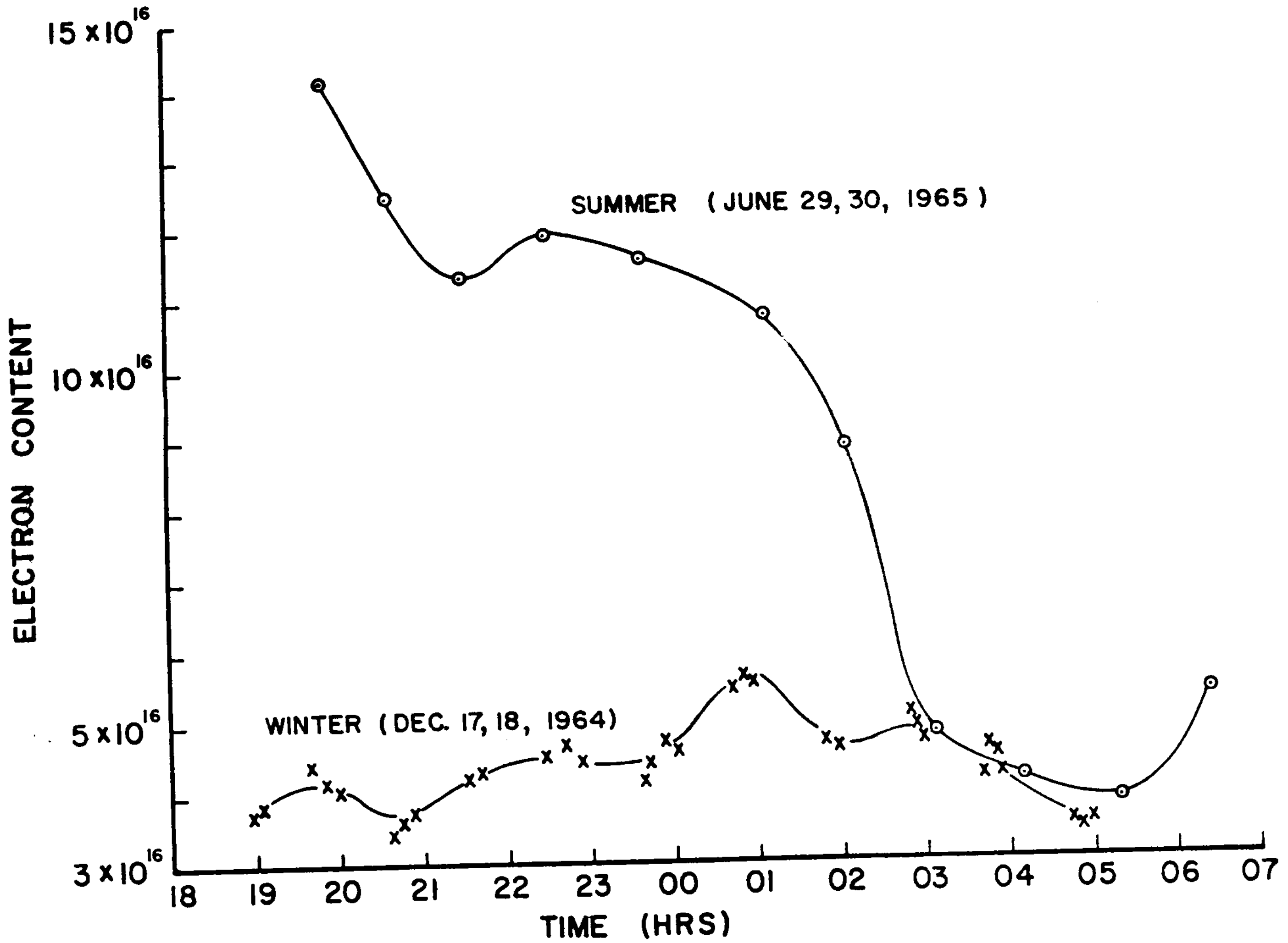
$$D = \frac{0.77 \times 10^{19} \sqrt{T} \, \mathrm{Sin}^2 I}{n(M)} \quad m^2 \, sec^{-1} \qquad [20:40 \text{ hrs} - 6/30/65]$$

From the limited number of examples calculated to date the indications are that the diffusion coefficients agree with those estimated based on the ionograms as previously corrected. However, the results of the incoherent scatter measurements to date are only for two nights in summer under low sunspot conditions.

2.2.3 Recombination During Summer

Figure 6 shows the total electron content as a function of time during one summer and one winter night. It is apparent that on the winter night in particular the electron content did not decrease and in fact does increase during a major portion of the night.

During the summer night (June 29, 1965) the electron content decrease was large from 20:00 to 21:30 hours and the recombination coefficient was calculated. Table II on page



ELECTRON CONTENT VS TIME

FIGURE 6

36 shows recombination coefficients calculated for four values of the quadratic loss coefficients for various times throughout the night.

It is apparent that there is approximately a factor of seven difference between the recombination coefficients calculated at 20:40 and 21:30 hours for $\alpha = 1 \times 10^{-15}$. However, if one looks at the change in electron content for the night in question (Figure 6), it becomes clear that the observed variations in the recombination coefficient were brought about by a drastic change in the rate of electron decay which began at approximately 21:30 hours.

It is felt that the drastic change in electron decay observed on this night is not representative of the usual summer night behavior and may have been caused by a moving disturbance over the observatory, but more data will be needed for other days to either prove or disprove this theory.

2.2.4 Recombination During Winter

In winter it is apparent that the integrated electron content did not in fact decrease during the night. It is thus not possible to explain this behavior on the basis of a decaying layer alone but it is important to make an estimate of the amount of production or ion flux into the region required to explain the observed behavior. This was done by considering the day as a whole.

Table II

Recombination Coefficients (β) for June 29, 30, 1965

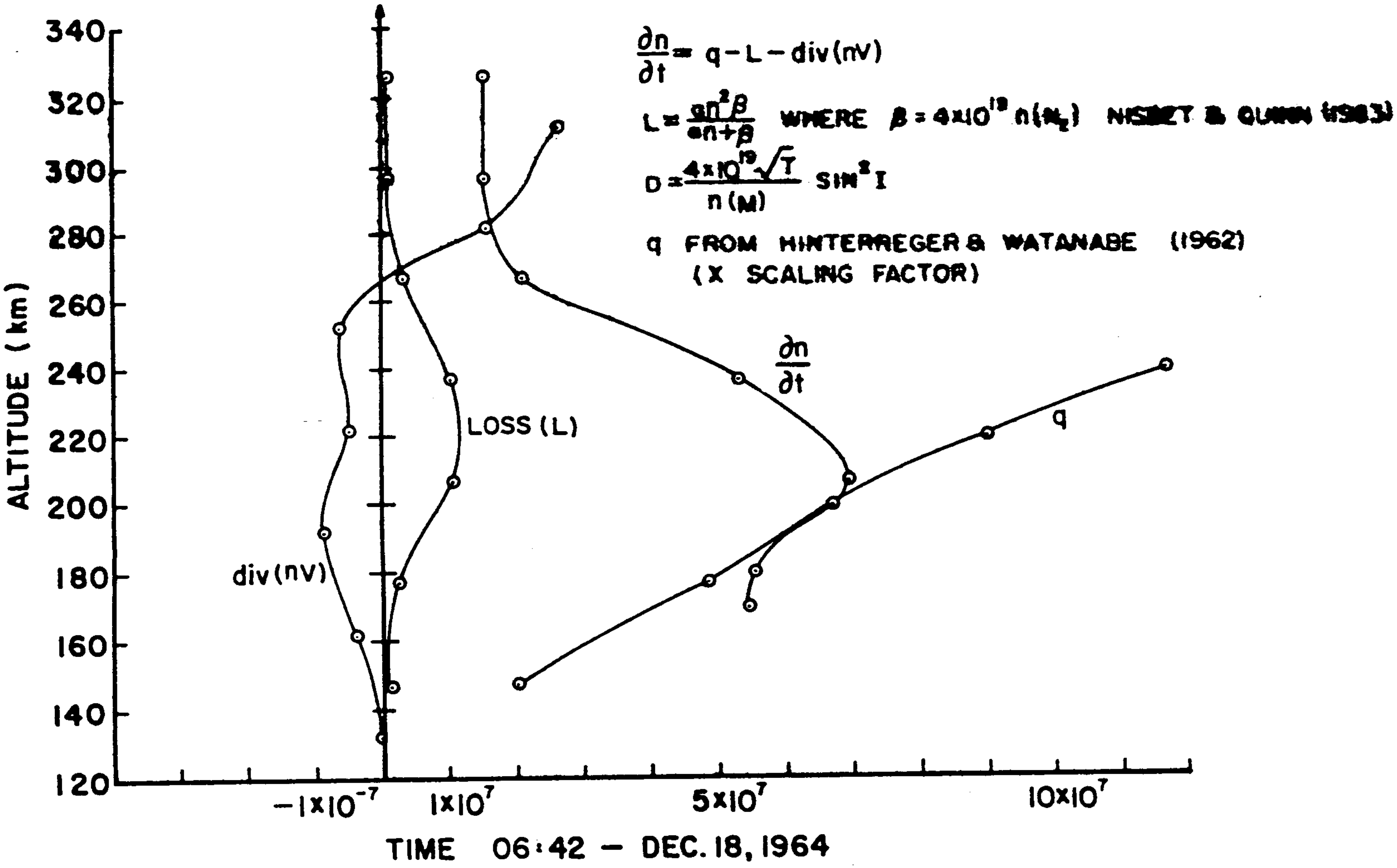
Time \ α	1×10^{-15}	3×10^{-15}	1×10^{-14}	3×10^{-14}
20:40	1.036×10^{-4}	7.002×10^{-5}	5.394×10^{-5}	4.670×10^{-5}
21:30	1.364×10^{-5}	1.137×10^{-5}	1.009×10^{-5}	0.946×10^{-5}
23:40	1.375×10^{-5}	1.139×10^{-5}	1.020×10^{-5}	0.968×10^{-5}
01:10	1.863×10^{-5}	1.385×10^{-5}	1.169×10^{-5}	1.082×10^{-5}
02:05	5.351×10^{-5}	2.994×10^{-5}	2.140×10^{-5}	1.832×10^{-5}
03:10	1.076×10^{-4}	4.961×10^{-5}	3.071×10^{-5}	2.414×10^{-5}
04:10	5.597×10^{-5}	3.335×10^{-5}	2.319×10^{-5}	1.871×10^{-5}

Shortly after sunrise, the production and rate of change of electron density terms predominate in the F1 region continuity equation. It is therefore possible to determine the production profile at that time in the region of 200 km even if the diffusion and recombination coefficients are not assumed to be known within an order of magnitude. Figure 7 shows profiles of the terms of the continuity equation at 6:42 hours calculated using data from the incoherent scatter sounder. The recombination coefficient values chosen for these calculations were taken from Quinn and Nisbet (1965). The diffusion coefficient was chosen to be

$$D = \frac{4.0 \times 10^{19} \sqrt{T} \ \mathrm{Sin}^2 I}{n(M)} \qquad (m^2 sec^{-1}),$$

a purposely high estimate. It is apparent that the loss and diffusion terms are small in the region of 200 km compared with the observed values of dn/dt. Watanabe and Hinteregger (1962) have presented production functions for various zenith angles. These were the functions used to represent the production rate at a solar zenith angle of 85° (i.e. near sunrise) along with an appropriate scaling factor (.644 in this instance).

The time period around 13:00 hours was next examined. It had been determined that at this time the region was stable at all heights and that it could therefore be assumed that the production and loss terms would be approximately in balance. The production at this time was then calculated using the same



CONTINUITY EQUATION TERMS

FIGURE 7

scaling factor as had been used for the dawn measurement. This resulted in a total integrated production at 13:00 hours of

$$\int q\,dz = 1.30 \times 10^{+14} \text{ electrons } m^{-2} sec^{-1}.$$

Using this production rate a value for the recombination coefficient was estimated to be

$$\beta_{300} = 1.98 \times 10^{-4} \text{ sec}^{-1}.$$

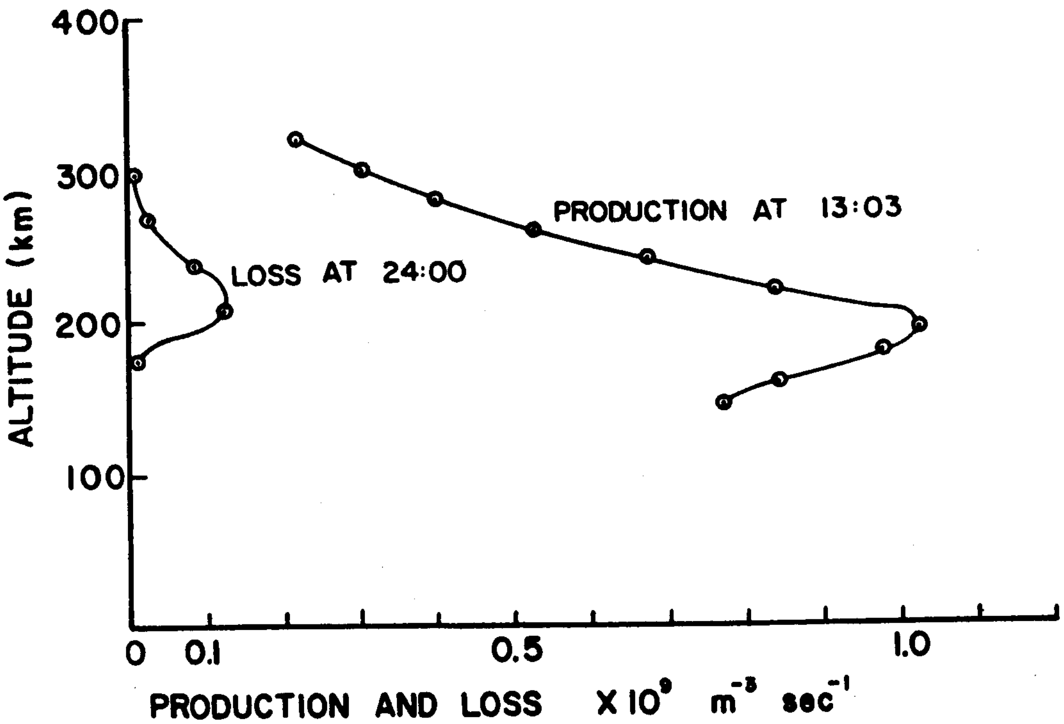
Based on the recombination rate estimated at 13:00 hours the recombination rate was calculated as a function of height at midnight using neutral atmospheric models due to Nicolet (1961).

Figure 8 shows the estimated production at 13:00 hours and the estimated loss at midnight calculated in the manner described. It is apparent that the total production required to maintain the nighttime ionosphere in winter is approximately five per cent of that present during the day. From these calculations it is estimated that on the night investigated a total production of the order of

$$\int q\,dz = 7.50 \times 10^{12} \text{ electron } m^{-2} \text{ sec}^{-1}$$

would have been sufficient to maintain the observed electron densities.

During the night in question, the ionosphere in the conjugate region was illuminated continuously at heights above 300 km and there would therefore be a continuous flux of



DEC. 17, 18, 1964

FIGURE 8

photoelectrons from this region. A large percentage of these electrons would have sufficient energy to ionize atomic oxygen and the fluxes which are required to explain the pre-dawn increase in electron temperatures are by no means negligible as an input flux. It is of course not possible to continually supply electrons during the night from one end of a field line to the other without either introducing a corresponding flux of ions, providing an equalizing current flow, or building up an electric field.
The electrons do come over as is indicated by the large increase in heating at high altitudes whenever the solar zenith angle at the conjugate area is less than 93°.

3. Results of the Analysis

3.1 Seasonal Dependence of Recombination Coefficient

For the summer night at 24:00 hours, β_{300} would have been approximately 5.0×10^{-5} sec^{-1} if the effects of the moving disturbance as previously noted were taken into consideration. Winter night calculations, as previously described, have yielded a β_{300} of 4.16×10^{-5} sec^{-1} for 24:00 hours. The winter values were derived in a very different manner from the summer values and depended on a knowledge of the diurnal variation of the neutral atmosphere which is only marginally available at present. Any difference between the two measurements cannot therefore be regarded as significant. Various factors were discovered that would cause errors in the previous analysis based on reduced ionograms. More work therefore remains to be done before a definite statement can be made on this point.

3.2 Diffusion Coefficient

Based on the assumption of a height independent drift component and a diffusion component alone being responsible for the total velocity, the diffusion coefficient was calculated for two consecutive nights during the summer at approximately 20:40 hours. A best estimate would be

$$D = \frac{(0.5 \pm 0.25) \times 10^{19} \sqrt{T}}{n\,(M)} \mathrm{Sin}^2 I \; (m^2 sec^{-1}).$$

The "drift velocities" in both instances were observed to be approximately 5 m/sec with "diffusion velocities" on the order of 10 m/sec.

4. Summary and Conclusions

4.1 Comparison with Previous Results

4.1.1 Electron Density Profiles and Ionospheric Temperatures

Evans (1965, a, b, c, d) has done some extensive ionospheric research using the backscattering technique at the Millstone Hill Radar Observatory. Evans (1965 c) has found that the electron temperatures remained larger than the ion temperatures throughout the night in winter, indicating a source which was preferentially able to heat the electrons. In the present work it was found that the electron temperature was higher than the ion temperature at night when the conjugate region was sunlit. T_e and T_i decreased continuously until 23:00 hours.

Evans (1965 d) has pointed out that three methods of measurements (radar backscatter, rockets, and satellites) have indicated that at night T_e increases monotonically with altitude and that $T_e > T_i$ both at night and during the day. From the present results however one can only conclude that at night during the winter T_e is essentially equal to T_i in the F-region. In the summer, however, $T_e > T_i$ at some altitudes during the night. T_e was found to increase monotonically with altitude.

4.1.2 Recombination Coefficient

The present result for a summer night of β_{300} of 5.0×10^{-5} sec^{-1} at 750° K may be compared with the value obtained by Quinn and Nisbet (1965) of $[2.1 \pm 2] \times 10^{-5}$ sec^{-1} at 750° K.

It was shown that in winter under low sunspot conditions the nighttime F-region cannot be adequately explained on the basis of a decaying layer and that it was necessary to assume a nighttime production or influx of the order of 7.5×10^{12} electrons m^{-2} sec^{-1} to make up for recombination compatible with daytime observations.

The winter results of Quinn and Nisbet (1965) are thus too low. Two of the effects they postulated to explain their low values have been confirmed. It was shown that the electron temperature does indeed decrease continuously prior to midnight and the atomic oxygen layer was observed to be compressed by the continual lowering of the altitude at which atomic hydrogen ions were observed to predominate. Neither of these causes was found to be sufficient, however, to explain the low results again in confirmation of the previous analysis.

The present study is not adequate to provide an answer on the possible seasonal variation of the nighttime recombination coefficient.

4.1.3 Diffusion Coefficient

Quinn and Nisbet (1965) reported a value for the diffusion coefficient of

$$D = \frac{(0.5 \pm 0.3)\, 10^{19} \sqrt{T}}{n(M)} \; \mathrm{Sin}^2 I \quad (m^2 sec^{-1})$$

Various values for the constant in the above equation have been reported and a few of these are listed in Table III below.

TABLE III

Comparison of Diffusion Constants

$D\, n(M)/\sqrt{T}$ $cm^{-1}\ sec^{-1}$	Author
4.5×10^{17}	Shimazaki (1957)
2.07×10^{17}	Cowling (1945)
4.30×10^{17}	Dalgarno (1964)
$(0.50 \pm 0.3) \times 10^{17}$	Quinn & Nisbet (1965)
$(0.50 \pm 0.25) \times 10^{17}$	Present Study

Hanson (1966) has commented that Dalgarno's values must be multiplied by a factor of 2 in order to represent the ambipolar diffusion case. In Table III above, Hanson's factor of 2 has been included in Dalgarno's results. Hanson (1966) also stated that Quinn and Nisbet's (1965) results were too low as a result of the corrections they applied to their profiles low down. The present study, however, required no corrections to the profiles low down other than the observed T_e/T_i ratio correction.

Based on the neutral atmospheric models of Nicolet (1961), a value for the diffusion coefficient of

$$D = \frac{(0.5 \pm 0.25) \times 10^{19}\sqrt{T}}{n(M)} \ \mathrm{Sin}^2 I \quad (m^2 sec^{-1})$$

was obtained in this study. This is in good agreement with the value previously obtained by Quinn and Nisbet (1965) using the same method of analysis and the same models of the neutral atmosphere. It thus appears that the discrepancy between the experimental results and the theoretical and laboratory values is not due to the corrections applied to the ionosonde reduced profiles but is either a real effect or a result of an assumption used in the analysis.

The simple assumption used in this and the preceding analysis using the same technique was that only two components of the vertical velocity were present, a vertical velocity independent of altitude called the drift velocity and a second component varying in altitude in the same manner as the diffusion term in the continuity equation. This assumption is probably a considerable simplification of the actual conditions. Neutral atmospheric winds are no doubt present on the night side of the earth. They appear to have been observed by satellites [King-Hele (1965)] and have been investigated theoretically by King and Kohl (1965), Geisler (1966) and Volland (1966). Such winds will be height dependent and will be lower at 230 km than at 335 km and could thus considerably influence both the estimates of the diffusion coefficient and the uniform drift velocity if they were present.

As pointed out by Quinn and Nisbet (1966) the estimations of the diffusion coefficient, granted the assumptions on which the calculations are based, are only as accurate as the neutral atmospheric models. As has been shown by Stein and Walker (1965), there is considerable latitude in the choice of neutral atmospheric models which will fit satellite data, and satellite retardation and gage measurements made on the same vehicle have shown differences in density measurements of a factor of 2.

The assumptions upon which the total ion velocity calculations are based are less extensive particularly at times when the layer is decaying rapidly. At such times, the transport and loss terms predominate in the continuity equation and the major sources of error are related to the loss estimates. Figure 9 shows the profiles of total velocity that would be obtained for the calculated value of recombination compared with values obtained if these are assumed to be 50 per cent higher or lower than calculated. It is apparent that the actual values are changed by approximately 20 per cent and that the general shape of the velocity profile remains unchanged in the vicinity of the peak and above.

4.2 Conclusions

The results of the present analysis compare very closely with those obtained by Quinn and Nisbet (1965) with the exception of the winter time recombination coefficients as pointed out previously. Due to the close agreement between the two works that was observed, it is felt that many of the assumptions made in the previous work were valid. Some of these assumptions will be discussed in the succeeding paragraphs.

4.2.1 Shape of the Top Profile

In this analysis, data was available which extended from below the maximum to approximately 1000 km. The top of the profile is therefore readily obtainable from the measurements made and hence no assumptions had to be made about what shape the top profile should assume. It was determined that in winter the scale heights changed steadily up to midnight and

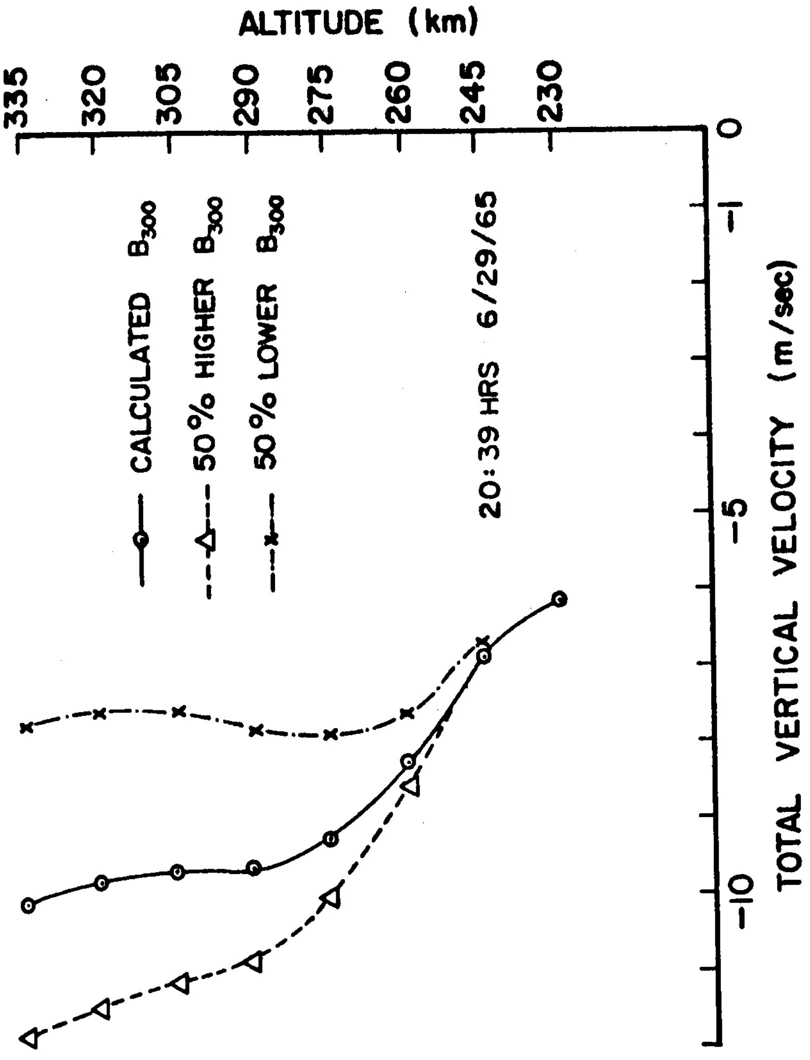

ALTITUDE (km)
335
320
305
290
275
260
245
230
0
-1
-5
-10
TOTAL VERTICAL VELOCITY (m/sec)
CALCULATED B_{300}
50% HIGHER B_{300}
50% LOWER B_{300}
20:39 HRS 6/29/65

FIGURE 9

that in consequence the winter recombination coefficients were underestimated in the previous analysis.

4.2.2 Determining Temperatures from the Profiles

It was not necessary to determine the temperatures from the profiles as previously done by Quinn and Nisbet (1965) since the backscattered spectra give directly a measurement of the ion temperature and T_e/T_i ratio.

It was shown in Figure 1, page 26, that on the winter night in question, the electron and ion temperatures began increasing at approximately 03:00 hours. Local sunrise, however, was not until approximately 06:42 hours. Carlson and Nisbet (1965) have shown that the time of this observed increase in temperature coincides with sunrise at the conjugate point and hence have set forth the idea that this heating is caused by photoelectrons from the conjugate ionosphere. Furthermore, the irregularity of the temperatures at the higher altitudes (300 and 375 km) throughout the winter night coupled with the observed increase in electron content throughout the night (Figure 6, page 34) lends some support to the idea of nighttime production during the winter. The conjugate ionosphere was illuminated at heights above 300 km throughout the night.

4.2.3 Quadratic Loss Coefficient

A value of 1×10^{-15} m^{-3} sec^{-1} for the quadratic loss coefficient provided the best agreement between the total and diffusion velocity profiles for both of the summer nights considered. This coefficient still seems to be the point of major uncertainty in this work as well as the previous one by Quinn and Nisbet (1965).

4.2.4 Low-Lying Ionization

Since such close agreement was found between the diffusion coefficient calculated in this work and that obtained by Quinn and Nisbet (1965), it does not seem that the method of compensating for low-lying ionization was a major source of error in the preceding work. Furthermore, Figure 3, page 30, has shown that recent ionosonde reduction methods [Doupnik and Schmerling (1965)] agree well with incoherent scatter profiles low down.

4.2.5 Change in T_e/T_i

During the summer night, the temperatures in the F-region were observed to decrease rather rapidly following sunset and then remain relatively constant until sunrise. The electron-to-ion temperature ratio was found to decrease to one by approximately 20:30 hours and remain close to one until sunrise the following morning at all altitudes with the possible exception of 300 km where it appeared the electron temperature remained above the ion temperature throughout the night. The total electron content for the summer night was found to decrease rather consistently throughout a major portion of the night.

The winter night on the other hand, showed a rather slow decrease in electron and ion temperatures throughout most of the night until conjugate point sunrise, at which time both the electron and ion temperatures began to increase. The electron content was found to increase throughout most of the night indicating a production mechanism was present. It was proposed that this production mechanism was photoelectrons from the conjugate ionosphere.

4.3 Suggestions for Further Research

The present work has been done considering only two days (one summer and one winter) under low sunspot conditions. Hence it is difficult to make conclusions concerning seasonal variations with this limited amount of data. Also, as more is found out about the neutral atmosphere, a more accurate estimate of the recombination and diffusion coefficients will be possible.

It is therefore suggested that this analysis be repeated using more data for both the summer and winter calculations. The variation in recombination and ion velocity with solar activity can also be investigated when this data becomes available in the future.

Subsequent investigations into ionospheric winds and drifts will be of significant importance in the accurate determination of ionospheric movements. For instance, if horizontal gradients are present this would have a direct effect upon any diffusion or vertical drift velocities observed. To date, most investigations have neglected horizontal gradients.

It would be profitable to investigate Arecibo's conjugate region using reduced ionograms and Nisbet and Quinn's (1963) method. Then comparisons could be made with data obtained at Arecibo at the same time. Some conclusions could then be drawn about nighttime production mechanisms.

Further research should also be done concerning the scattered high energy electrons from the Van Allen belt since these may have a direct effect upon the electron flux into the ionosphere and resultant heating of the F-region.

BIBLIOGRAPHY

Carlson, H. C. and J. S. Nisbet, "Electron Densities and Temperatures in the F-Region from Backscatter Measurements at Arecibo," Electron Density Profiles in Ionosphere and Exosphere, edited by Jon Frihagen, 1966.

Chandra, S. and R. A. Goldberg, "Geomagnetic Control of Diffusion in the Upper Atmosphere," J. Geophs. Res. 69, no. 15, pp. 3187-3197 (August 1, 1964).

Cowling, T. G., "The Electrical Conductivity of an Ionized Gas in a Magnetic Field with Applications to the Solar Atmosphere and the Ionosphere," Proc. Roy. Soc. A 183, pp. 453-479 (1945).

Dalgarno, A., "Ambipolar Diffusion in the F-region," J. Atmosph. Terr. Phys 26, p. 939 (September 1964).

Doupnik, J. R. and E. R. Schmerling, "The Reduction of Ionograms from the Bottomside and Topside," J. Atmosph. Terr. Phys. 27 , pp. 917-941 (August 1965).

Evans, J. V., "Diurnal Variation of the Temperature of the F-Region," J. Geophs. Res. 67 , No. 12, pp. 4914-4920 (November 1962).

Evans, J. V., "Cause of the Mid-Latitude Evening Increase in f_oF_2," J. Geophs. Res. 70 , No. 5, pp. 1175-1185 (March 1, 1965a).

Evans, J. V., "Midlatitude Ionospheric Temperatures on Magnetically Quiet and Disturbed Days," J. Geophs. Res. 70 , No. 11, pp. 2726-2732 (June 1, 1956b).

Evans, J. V., "Cause of the Midlatitude Winter Night Increase in f_oF_2," J. Geophs. Res. 70 , No. 17, pp. 4331-4345 (September 1, 1965c).

Evans, J. V., "A Comparison of Rocket, Satellite, and Radar Determinations of Electron Temperature at Midlatitudes," J. Geophs. Res. 70 , No. 17, pp. 4365-4374 (September 1, 1965d).

Fejer, J. A., "Scattering of Radio Waves by an Ionized Gas in Thermal Equilibrium," Canadian J. of Phys. 38 , pp. 1114-1133 (1960).

Ferraro, V. C. A., "Diffusion in the Ionosphere: A Review of Some Recent Work," Annales de Geophysique 17, pp. 82-89 (Jan-March, 1961).

Ferraro, V. C. A., "Some Remarks on Ambipolar Diffusion in the Ionosphere," J. Atmosph. Terr. Phys. 26, No. 9, pp. 913-917 (September 1964).

Garriot, O. K. and J. O. Thomas, "Some Numerical Solutions of the Continuity Equation for Electrons in the Nighttime F Region of the Ionosphere," J. Geophs. Res. 67, No. 11, pp. 4211-4219 (October 1962).

Garriot, O. K. and F. L. Smith III, "The Rate of Production of Electrons in the Ionosphere," Planet. Space Sci., 13, pp. 839-849 (August 1965).

Geisler, J. E., "Atmospheric Winds in the Middle Latitude F-region," J. Àtmosph. Terr. Phys. 28, pp. 703-720 (August 1966).

Gliddon, J. E. C. and P. C. Kendall, "Theoretical World Curves of Maximum Ion Density in a Quiet F-region," J. Atmosph. Terr. Phys. 18, pp. 48-59 (April 1960).

Gordon, W. E., "Incoherent Scattering of Radio Waves by Free Electrons with Applications to Space Exploration by Radar," Proc. IRE 46, pp. 1824-1829 (1958).

Hanson, W. B. and T. N. L. Patterson, "The Maintenance of the Night-time F-layer," Planet. Space Sci. 12, pp. 979-997 (1964).

Hanson, W. B., "Comment on a Paper by Thomas P. Quinn and John S. Nisbet, 'Recombination and Transport in the Nighttime F Layer of the Ionosphere'," Letter to the Editor of J. Geophs. Res. 71, No. 1, p. 348 (Jan. 1, 1966).

Harris, I. and W. Priester, The Upper Atmosphere in the Range from 120 to 800 km, NASA Goddard Space Flight Center Theoretical Division, Greebelt, Maryland and Institute for Space Studies, New York 27, New York, August 25, 1964.

Hinteregger, H. E. and K. Watanabe, "Photoionization Rates in the E and F Regions, 2," J. Geophs. Res. 67, No. 9, pp. 3373-3392 (August 1962).

Jacchia, L. G., "Variations in the Earth's Upper Atmosphere as Revealed by Satellite Drag," Smithsonian Astrophys. Obs. Rept., Cambridge, Mass. (December 1962).

Kendall, P. C., "Geomagnetic Control of Diffusion in the F2-region of the Ionosphere-I," J. Atmosph. Terr. Phys. 24, pp. 805-811 (September 1962).

Kendall, P. C., "On the Equations Governing Diffusion in the F2-Layer," J. Atmosph. Terr. Phys. 26, No. 5, pp. 624-626 (May 1964).

King, J. W. and H. Kohl, "Upper Atmospheric Winds and Ionospheric Drifts Caused by Neutral Air Pressure Gradients," Nature 206, pp. 699-701 (May 15, 1965).

King-Hele, D. G. and Eileen Quinn, "The Variation of Upper-Atmosphere Density Between Sunspot Maximum (1957-1958) and Minimum (1964)," J. Atmosph. Terr. Phys. 27, pp. 197-209 (February 1965).

Laaspere, T., "Comments on the Problem of Incoherent Scattering," Research Report RSI, Cornell University, 53 pages (December 15, 1959).

Long, A. R., "The Distribution of Electrons in the Nighttime Ionosphere," J. Geophs. Res. 67, pp. 989-997 (1962).

Martyn, D. F., "Atmospheric Tides in the Ionosphere: Part I - Solar Tides in the F2 Region," Proc. Roy. Soc. (London) A, 189, pp. 241-260 (April 17, 1947).

Martyn, D. F., "The Normal F Region of the Ionosphere," Proc. IRE 47, pp. 147-155 (1959).

Moorcroft, D. R., "On the Determining of Temperature and Ionic Composition by Electron Backscattering from the Ionosphere and Magnetosphere," J. Geophs. Res. 69, No. 5, pp. 955-970 (March 1, 1964).

Nicolet, M., "Density of the Heterosphere Related to Temperature," Smithsonian Astrophys. Observatory, Spec. Rept. 75 (September 19, 1961).

Nicolet, M. and W. Swider, Jr., "Ionospheric Conditions," Planet. Space Sci. 11, pp. 1459-1482 (1963).

Nisbet, J. S. and T. P. Quinn, "The Recombination Coefficient of the Nighttime F Layer," J. Geophs. Res. 68, No. 4, pp. 1031-1038 (February 15, 1963).

Pineo, V. C. and H. W. Briscoe, "Discussion of Incoherent Backscatter Power Measurements at 440 mc/s," J. Geophs. Res. 66, pp. 3965-3966 (1961).

Quinn, T. P. and J. S. Nisbet, "Recombination and Transport in the Nighttime F Layer of the Ionosphere," J. Geophs. Res. 70, No. 1, pp. 113-130 (January 1, 1965).

Quinn, T. P. and J. S. Nisbet, "Author's Reply," J. Geophs. Res. 71, p. 350 (January 1, 1966).

Ratcliffe, J. A., E. R. Schmerling, G. S. Setty, and J. O. Thomas, "The Rates of Production and Loss of Electrons in the F Region of the Ionosphere," Phil. Trans. A, 248, pp. 621-642 (1956).

Rishbeth, H. and D. W. Barron, "Equilibrium Electron Distribution in the Ionospheric F_2-layer," J. Atmosph. Terr. Phys. 18, pp. 234-252 (1960).

Rishbeth, H. and C. S. G. K. Setty, "The F-layer at Sunrise," J. Atmosph. Terr. Phys. 20, pp. 263-276 (1961).

Rishbeth, H., "Diffusion of Ionization in the Sunrise F-layer," J. Atmosph. Terr. Phys. 20, pp. 277-288 (1961).

Salpeter, E. E., "Electron Density Fluctuations in a Plasma," Phys. Res. 120, p. 1528 (1960).

Shimazaki, T., "Dynamical Structure of the Ionospheric F2 Layer," J. Rad. Res. Lab. 4, No. 17, p. 309 (July 1957).

Stein, Jay A. and J. C. G. Walker, "Models of the Upper Atmosphere for a Wide Range of Boundary Conditions," J. Atmosph. Sci. 22, pp. 11-17 (January 1965).

Watanabe, K. and H. E. Hinteregger, "Photoionization Rates in the E and F Regions," J. Geophs. Res. 67, No. 3, pp. 999-1006 (March 1962).

Willmore, A. P., "Energy Sources for the Ionospheric Electrons," Nature 202, No. 4927, pp. 41-42 (April 4, 1964).

Volland, H., "On the Dynamics of the Upper Atmosphere," COSPAR Vienna (May 1966).

Yonezawa, T., "On the Influence of Electron-Ion Diffusion on the Electron Density and Height of the Nocturnal F_2 Layer," J. Rad. Res. Lab. 2, pp. 125-136 (1955).

APPENDIX A

Suggested Summer and Winter Values for β *

T, deg K	Summer β	Winter β
1250	$[1.95 \pm 0.5]\ 10^{-4} \exp -\left[\frac{Z - 300}{33}\right] \sec^{-1}$	$[0.9 \pm 0.3] 10^{-4} \exp -\left[\frac{Z - 300}{33}\right] \sec^{-1}$
1025	$[1.11 \pm 0.4]\ 10^{-4} \exp -\left[\frac{Z - 300}{27}\right] \sec^{-1}$	$[0.35 \pm 0.2] 10^{-4} \exp -\left[\frac{Z - 300}{27}\right] \sec^{-1}$
750	$[0.21 \pm 0.2]\ 10^{-4} \exp -\left[\frac{Z - 300}{20}\right] \sec^{-1}$	$[0.65 + 2.0, -0.64] 10^{-5} \exp -\left[\frac{Z - 300}{20}\right] \sec^{-1}$

*Quinn and Nisbet (1965)